Chapter 14

End-Fire Mode Spectroscopy: A Measuring Technique for Optical Waveguides

Dmitry V. Svistunov

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.75558

Abstract

End-fire mode spectroscopy technique provides reliable measurement of the whole mode spectrum of optical waveguides having arbitrary cross refractive index profile. The method is based on registration of light beams radiated from the abrupt output edge of the waveguide, with each beam corresponding to the individual waveguide mode. Due to different values of mode propagation constants, modes of different orders demonstrate different refraction angles at the output waveguide face when modes reach that face under the same nonzero inclination angle. Just this feature is used in the technique. Mode excitation is performed directly through the input waveguide face, and therefore the technique can be applied to analyze mode spectrum of arbitrary waveguides, including the ones with non-monotonic index profiles (particularly, symmetric step-index profiles or buried graded-index waveguides with any burying depths).

Keywords: waveguides, integrated optics, mode index, refractive index, optical measurements

1. Introduction

Optical waveguides are the basic elements of any photonic device, and their parameters define the operating performances of the whole photonic unit. Optimization of those parameters requires performing the choice of appropriate technology conditions. Development of fabrication technology and further designing the waveguide elements having pre-defined properties need performing a control of the characteristics of trial waveguide samples. Furthermore, planar optical waveguides are used intensively in determination of the basic properties of optical materials. And the problem of reliable determination of the main waveguide performances is still actual.

Important part of examination of planar optical waveguides is measurement of the waveguide mode spectrum. Usually this procedure is performed by a well-known m-line spectroscopy technique (e.g., see [1–5]). The measured set of mode indices can be considered as initial data as for preliminary determination of the device operating performances as for reconstruction of cross refractive index profile in the formed trial sample. Traditional computing techniques allowing reconstruction of that profile are described in Refs. [6, 7]. However, in cases of planar waveguide structures with thick cover layers or so-called buried graded-index waveguides m-line spectroscopy does not provide reliable measurements. Thick cover layers or large burying depths do not allow tunneling the modes to the external prism and forming the corresponding spatial m-lines. In these cases, some modes (first of all, the lower-order modes) may be simply missed in examinations by m-line spectroscopy [8, 9]. The greater the burying depth the fewer number of modes can be measured by this method. To avoid missing the modes, a layer-by-layer etching of the sample surface could be applied [10, 11]. However, that procedure has many chances to cut a part of the refractive index profile occupied by the mode fields, and that should lead to distortion of the original waveguide mode spectrum. The use of nonlinear optical effects like second harmonic generation [9] can be successful only for limited number of optical materials demonstrating high values of the corresponding coefficients.

Here we describe a measuring technique named the end-fire mode spectroscopy which is suitable for examination of planar waveguides having arbitrary refractive index profiles including the case of buried waveguide structures with any burying depths, and the presented results of examination of buried waveguides prove this advantage of the technique. Furthermore, here we show that this technique allows also conducting direct measurements of another important characteristic – the maximal refractive index in graded-index waveguides, unlike conventional techniques that involve the set of measured mode indices and employ computing of the maximal value in the refractive index profile using different approximations.

2. Method content

2.1. Mode spectrum measuring

Usually waveguide mode spectrum is presented with a kit of mode indices N_m (the value obtained from the mode propagation constant β_m as $N_m = \beta_m /k$, where $k = \omega /c = 2\pi /\lambda$; ω, c and λ – the light frequency, velocity and wavelength in vacuum correspondingly, m – the mode number). These values relate to the mode phase velocity, and they are involved into expressions describing the mode fields which are derived as solutions of wave equations. We can write a well-known general form of such expression for mode electric field vector (magnetic component of light wave is of the same view): $\mathbf{E_m}(x,y,z,t) = \mathbf{E}_0(x,y) \times \exp[i(\omega t - \beta_m z)]$. That representation is applied for all kinds of waveguides: planar and 3D (including stripe and channel waveguides, fibers, etc.) having as different step-like cross index distributions as graded-index ones. The expression written in cylindrical coordinates has a similar view (that approach is more convenient for optical fibers). Depending on the mode type, corresponding nonzero field projections are considered. Evidently, that expression describes unidirectional propagation of light wave having some cross field distribution. That description means that the waveguide mode is represented by the equivalent model of plane wave propagating in homogeneous uniform medium with the same light phase velocity as the original waveguide mode. So, we can consider a waveguide transmitting several modes as an imaginary set of superimposed layers with uniform refractive indices N_m, each denoting the certain waveguide mode and transmitting the plane wave having corresponding cross field distribution as it is shown in **Figure 1**. Then our aim (to measure the mode spectrum) can be associated with the task of measuring the indices of different uniform media illuminated with plane light waves. That task can be performed by the technique like one of the usual methods of traditional bulk refractometry, for example by the goniometric technique that bases on the Snell's law and employs registration of the beam declination angle when the prism of tested optical material is illuminated with the collimated incident light. Thus we could try to provide similar experimental conditions in order to examine the waveguide samples.

The content of the end-fire mode spectroscopy is registration of light beams radiated from the abrupt output edge of a planar waveguide, with each beam corresponding to the individual waveguide mode. Due to different values of mode propagation constants, modes of different orders demonstrate different refraction angles at the output sample face if they are directed to that face under nonzero incidence angle into the waveguide. Just this feature is exploited by the technique in procedures of mode spectrum measurements. Both excitation and output of waveguide modes are performed at the sample faces by the end-fire coupling method which allows reliable launching and output of the whole mode spectrum in any planar waveguide. Therefore, the end-fire mode spectroscopy technique can be applied to examination of planar waveguides having arbitrary cross refractive index profiles including symmetric step-index ones and deep-buried graded-index waveguides.

The measuring block-scheme is shown in **Figure 2**. Collimated light beam is focused on the input waveguide face by the cylindrical lens. The whole mode spectrum can be launched in this manner in few-mode waveguides. Application of the input cylindrical lens provides obtaining collimated (in the sample planform) mode beams propagating into the examined waveguide. In the case of a thick multimode waveguide, a group of modes is excited simultaneously and can be registered. Further scanning the input sample face along the Y axis allows launching and registration of other mode groups until the whole waveguide mode spectrum is measured.

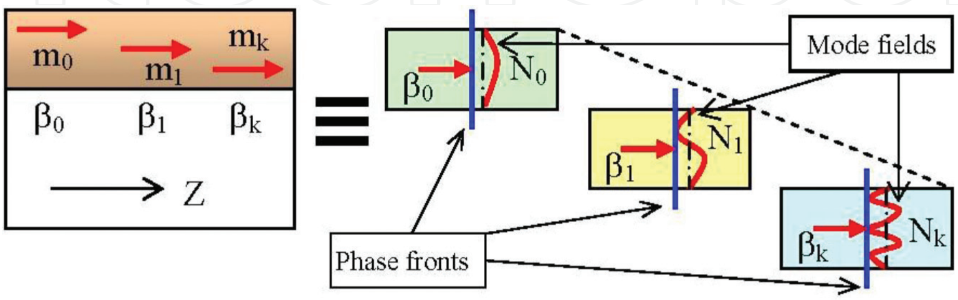

Figure 1. Equivalent representation of graded-index planar waveguide as a set of superimposed layers having uniform refractive indices.

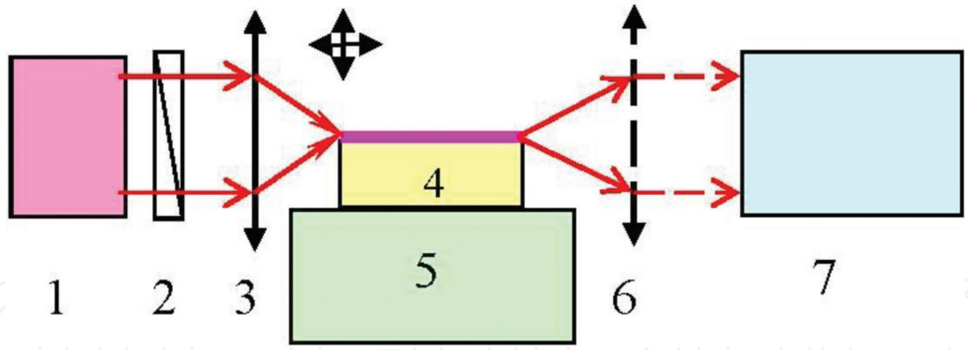

Figure 2. Measuring block-scheme. 1 – Laser with collimator, 2 – Polarizer, 3 and 6 – Cylindrical lenses, 4 – Examined waveguide sample, 5 – Goniometer sample mount, 7 – Goniometer telescope.

Cylindrical lens in the recording block is not necessary for measuring the mode spectrum. That lens should be installed in procedures of complex measuring as described below.

Two scheme variants providing skew incidence of waveguide beams to the sample output face have been proposed [12]. The former one uses the trapezoidal (in planform section) samples having non-parallel opposite (input and output) waveguide faces as it is shown in **Figure 3**. The latter one allows testing the samples having usual rectangular form with mode launching performed under special procedure by focusing the probe beam on the polished side face of the examined waveguide. Application of a cylindrical lens for mode excitation enables obtaining collimated (in planform XZ section) waveguide beams in both scheme variants. The latter variant is very attractive because of its non-destructive character, but the alternative former scheme is more convenient for conducting measurements.

The optical scheme has been built according to the former measuring variant in our experiments, and **Figure 3** demonstrates light ray paths in planform XZ section of the sample. Whereas the directions of simultaneously excited modes slightly differ due to different refraction at the input sample face, the rays of only one mode beam are shown into the waveguide in order to simplify the drawing. Each output light beam is associated with the individual waveguide mode, and the mode orders of the corresponding modes are identified by the

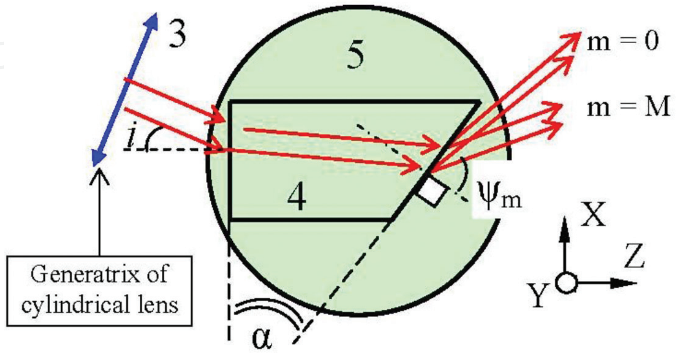

Figure 3. Planform of the sample on the goniometer mount. Two-sided arrow denotes here the cylindrical lens generatrix; other designations are the same as in **Figure 2**.

inclination of a certain output beam to the output waveguide face: the lower the mode order, the bigger the output angle. The fundamental mode forms the light beam having maximal value of the output angle ψ_{max}. In the upright YZ projection, the output beams have large divergence (see **Figure 2**). Therefore, these beams appear on the cross screen apart of the sample as separate light strips.

Application of the Snell's law both to input and output sample faces leads to following expression for calculating the mode indices N_m:

$$N_m = \sqrt{(\sin \psi_m / \sin \alpha + \sin i / \tan \alpha)^2 + (\sin i)^2} \quad (1)$$

where m is the mode order, i and ψ_m are the incident and output angles of the spatial light beams measured in the XZ plane, and α is the angle between the input and output waveguide faces.

Evidently, normal incidence of the probe beam to the input waveguide face (i.e., the condition $i = 0$) is the simplest scheme variant that is most suitable for measuring. For such scheme, Eq. (1) transforms to.

$$N_m = \sin \psi_m / \sin \alpha \quad (2)$$

When graded-index waveguides are examined, the pattern of output beams has a specific view as a set of slightly curved light strips on the cross screen. The simplest way to explain that pattern is application of the known ray approximation of waveguide light propagation. Following to that approach, **Figure 4** demonstrates the rays into shallow graded-index planar waveguide. All drawn rays represent the same waveguide mode.

One can see that the ray 3 is radiated being parallel to the sample surface from the output face point with the depth of so-called turning point which corresponds to the depth in the refractive index cross distribution where the mode index is equal to the refractive index value. So, just the direction of that ray in the planform XZ plane should be registered in measuring the waveguide mode spectrum. The ray scheme demonstrates also the rays 2 and 4 radiated from arbitrary point of the output face under equal opposite tilts. The presence of those rays means

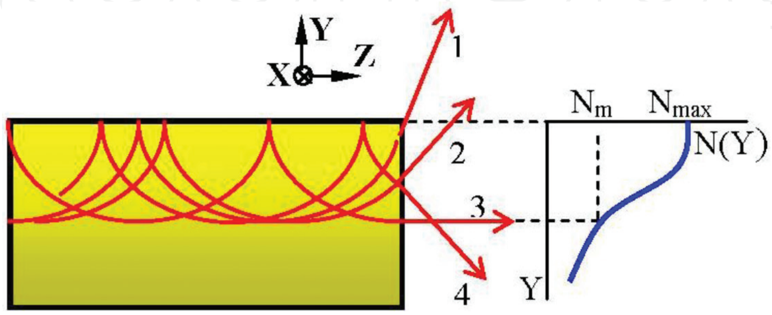

Figure 4. Ray approximation of mode propagation into graded-index planar waveguide. All plotted rays represent the same mode.

that the output light beam is symmetric relatively to the ray 3. Furthermore, the rays 1–3 are radiated from the sample points at different depths where the refractive index has different values. Therefore, the projections of those output rays to the planform XZ should have different directions in that plane. Thus the pattern of the output light beam (corresponding to the certain waveguide mode) on the cross screen apart the sample looks like a curved light strip which is symmetric relatively to the waveguide surface as it is shown in **Figure 5**. As we must register the rays that are analogous to the ray 3, we find those rays at the top of parabolic-like light strip.

Reliability of the results of mode spectrum measuring by the end-fire mode spectroscopy was proved in comparative examinations of graded-index planar waveguides fabricated in optical glasses. The mode spectrum of the same waveguides had been measured independently with the described technique and also by the traditional m-line spectroscopy method. Whereas the main advantage of the end-fire spectroscopy is its capability to analyze buried waveguides, several shallow graded-index samples had been chosen for comparative measuring because the traditional technique provides reliable results only for that type of waveguides.

Figure 6 presents the photo of the typical pattern formed by output light beams on the cross screen apart from the sample in examinations by the end-fire mode spectroscopy.

The whole spectrum of TE modes was launched simultaneously in this experiment, and the light strips really demonstrate some curvature due to the cross graded-index profile in the examined waveguide layer (see **Figure 6a**). The centers of the parabolic-like light curves were used for measuring the output angles ψ_m. The enlarged view of those central parts of the light strips (**Figure 6b**) demonstrates good separation of the strips. So, they can be easily registered in measuring.

As an example, **Table 1** presents the results of comparative examinations of the planar waveguide fabricated on the substrate of commercial sodium-containing glass K8 by ion exchange in a potassium nitrate melt at 400°C. The probe light of 633 nm wavelength was used, and the bevel angle between the opposite sample faces was measured with the goniometer by the autocollimation method as $\alpha = 38^0\ 57'\ 08'' \pm 5''$.

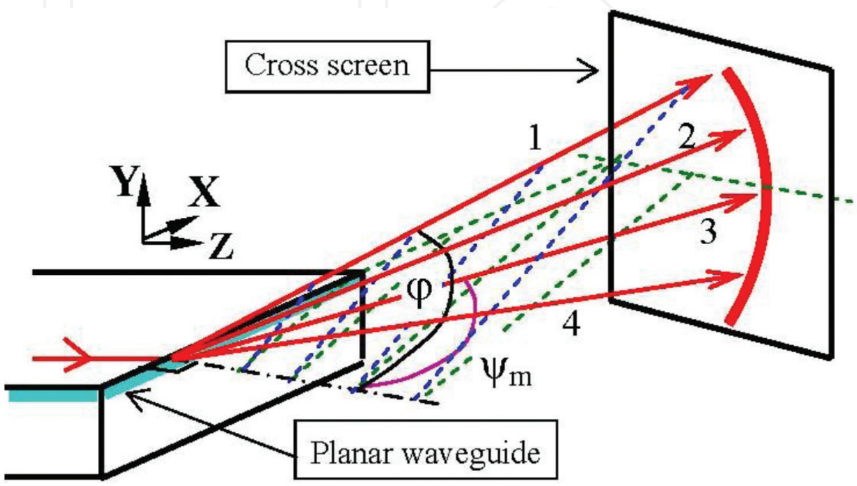

Figure 5. Spatial light beam radiated from the output waveguide face.

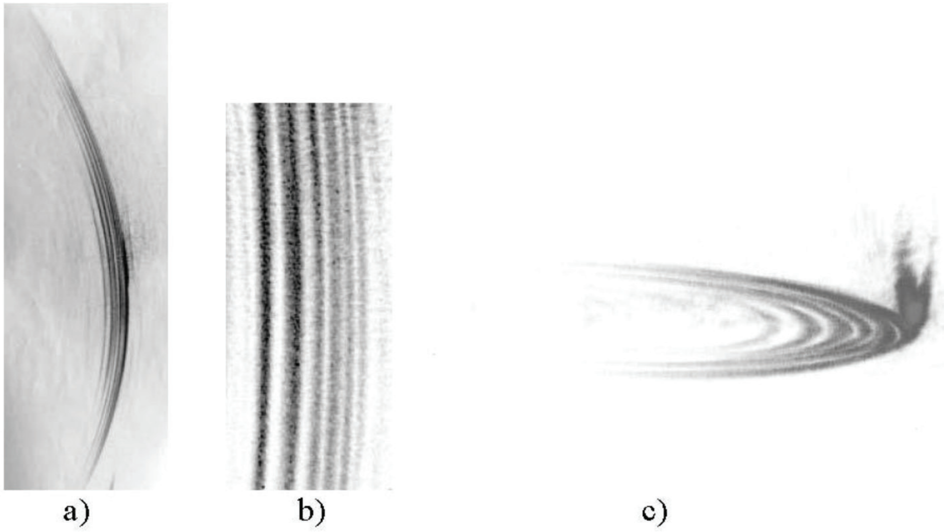

Figure 6. Photos of the patterns on the cross screen in procedures of mode spectrum measuring (a, b) and in complex measuring (c). λ = 633 nm, planar K8:K+ waveguide. (Here all photos – Negatives, colored positives – In online version).

Mode order	0	1	2	3	4	5	6
m-line spectro-scopy	1.51980	1.51822	1,51701	1.51611	1.51544	1.51493	1.51452
End-fire mode spectro-scopy	1.51985	1.51824	1.51711	1.51619	1.51549	1.51494	1.51456

Table 1. Comparative examination of planar K8: K+ waveguide, TE modes, λ = 633 nm.

A good agreement between the mode index values measured by both techniques is evident. The difference between the results obtained by those methods does not exceed 10^{-4}, which is similar to the errors considered quite acceptable in traditional mode index measurements.

Furthermore, the samples of buried waveguide structures have been tested by the end-fire spectroscopy technique. Planar buried waveguides have been formed in optical glasses by two-staged ion exchange. First, the shallow planar waveguides having the maximal refractive index at the sample surface were fabricated. Then the samples were treated into another melt providing appearance of reverse direction of diffusion process into the sample. That procedure led to decreasing the surface refractive index while the maximum of the cross index distribution was shifted deeper to the sample depth. Performed choice of the stage's durations resulted in fabrication of buried waveguide structures.

Mode excitation was performed in examinations by focusing the light beam to the input sample face. However, no waveguide modes have been registered in examinations of those structures by traditional m-line spectroscopy while both direct watching and application of 40^x

and 90^x objectives proved the presence of the mode light spots at the output sample face. That means that the obtained burying depths were sufficient for the case when the "tails" of mode field distribution were so weak near the sample surface that their tunneling to the prism did not resulted in appearance of the output light beams which could be registered. Application of the end-fire mode spectroscopy technique allowed analyzing the waveguide structures that supported propagation of single TE mode. The results of performed examinations by the described technique are presented in **Table 2**.

Thus, the end-fire mode spectroscopy technique has demonstrated successfully its advantageous feature that is capability of examination of planar structures of any type.

2.2. Evaluation of maximal refractive index

Besides mode spectrum measuring, the technique enables evaluating the maximal refractive index in graded-index waveguides. A principle of that procedure can also be explained involving ray approximation of mode propagation. One can conclude from **Figure 4** that we should register the ray 1 radiated from the waveguide at the sample point having maximal refractive index in the graded-index layer. Determination of that index is performed using the output angle φ of that boundary ray of the emitted light beam. That angle is marked in **Figure 5**, and we see that it must be measured in the plane formed by both the considered ray and the normal to the output sample face, and that plane is tilted to the planform XZ plane. Ray tracing performed for that boundary ray shows that the maximal refractive index N_{max} can be determined by solving Eq. [13].

$$N_{max} \cdot \cos\left\{\arcsin\left[\left(N_m / N_{max}\right)\cos\alpha\right]\right\} = \sin\varphi \qquad (3)$$

However, in our optical scheme the goniometer measures the angles lying in the XZ plane. So, we obtain in our measuring the values of the angle φ_{xz} which is the projection of the angle φ to the XZ plane, and the relation between those angles should be used in calculations. Another circumstance to be considered is following: both angular and linear apertures of the goniometer telescope are limited, but the registered beam is high-divergent in the upright projection YZ. Therefore, we should apply the cylindrical lens (drawn by dash line in **Figure 2**)

Sample	K8 : K^+ : Na^+	K8 : K^+ : Na^+	K8 : Ag^+ : Na^+
Stage 1 of treatment	Melt: KNO_3 400 ºC ; 24 hrs	Melt: KNO_3 400 ºC ; 24 hrs	Melt: 0.5% mol. KNO_3 + 99.5% mol. eut. (K – Na)NO_3 348 ºC ; 24 hrs
Stage 2 of treatment	Melt: $NaNO_3$ 400 ºC ; 19.5 hrs	Melt: $NaNO_3$ 400 ºC ; 15 hrs	Melt: $NaNO_3$ 348 ºC ; 15 hrs
Mode index	1.5156	1.5159	1.5162

Table 2. Examination of buried waveguides by end-fire mode spectroscopy, TE_0, λ = 633 nm.

http://dx.doi.org/10.5772/intechopen.75558

in the recording scheme block in order to collimate the measured light beam. Considering the parameters of the lens, relation between the mentioned angles can be deduced as.

$$\tan \varphi = \tan \varphi_{XZ} \sqrt{\left[1 + (d/2f)^2\right]\left[(N_{max}/N_m)^2 - (\cos \alpha)^2\right]} / \sin \alpha \tag{4}$$

where f is the focus length of the cylindrical lens, and d is the size of the output curved light strip measured along the Y axis behind that lens. Considering (4) and also a known relation $\sec^2\varphi = 1 + \tan^2\varphi$, one can deduce from (3) the final equation containing the only unknown N_{max}. Numerical solution of the obtained equation gives the desired value of the maximal refractive index in the graded-index waveguide.

It should be noted that mentioned collimation of the output beam is needed only in measurements of the maximal refractive index when one must register high-divergent boundary rays. Measurement of the mode spectrum is performed by registering the central parts of the output light beams, and it does not matter is the output cylindrical lens applied or not in that case.

As an example, let us consider the results of evaluation of the maximal refractive index in the K8: K^+ waveguide whose mode spectrum is presented above. The photo of the pattern of output light beam obtained in measuring by the described technique is shown in **Figure 6c**. For comparison, the maximal refractive index had been measured directly by the end-fire mode spectroscopy and also computed according to conventional methods using the measured mode spectrum. The White-Heidrich method [6] gives the result as $N_{max,WH} = 1.52204$, and the Chiang method [7] is resulted in $N_{max,Ch} = 1.52138$. So, these widespread computing techniques give different results for the same waveguide. Basing on the results obtained for waveguides of that type (see, for example, Ref. [14]), and also taking into account our previous experience we can guess that application of the White-Heidrich technique is more appropriate for reconstruction of refractive index profile in the examined sample because the used fabrication technology results in graded-index layers demonstrating cross refractive index distributions which are well described with the *erfc* function. Direct measuring conducted by the end-fire mode spectroscopy resulted in the value $N_{max} = 1.5223$ when the highest-order mode was registered. This value is evidently closer to the result of the White-Heidrich method than the solution of the Chiang method. It means that the described technique provides direct measuring of the maximal refractive index in graded-index waveguides with rather good accuracy. We must note that some imprecision occurs in measuring caused by diffractive character of real output light beams that defines smudgy ends of registered light strips and therefore impedes obtaining a high accuracy. However, the deviation of the measured result from the actual one is less than the difference (and, consequently, uncertainty) between the results computed according to traditional techniques. In any way, the obtained value is to be considered as the result of maximal index estimation and can be used as itself for further estimations of treatment conditions or waveguide unit performances, as for choosing between the noted traditional computing techniques of index profile reconstruction.

The pattern shown in **Figure 6c** demonstrates that application of the cylindrical leans in the scheme recording block really does not affect the central parts of light strips and allows conducting measurements of the mode spectrum also in that variant of optical scheme. So, the end-fire mode spectroscopy technique allows performing reliable direct complex measurements of the set of important optical characteristics of arbitrary planar waveguides (the mode spectrum and the maximal refractive index) in a single procedure.

3. Measuring conditions

3.1. Choice of the sample form

For enhancing the technique sensitivity and accuracy, we must consider the conditions providing maximal variation $\delta\psi_m$ of the light beam emission line related to mode index variation δN_m. Referring to Eq. (2), one can see that the value of the term $\partial\psi_m/\partial N_m = \sin\alpha/(1 - N^2_m \sin^2\alpha)^{1/2}$ increases with a rise in the bevel angle α between the opposite waveguide faces. So, in order to provide high method sensitivity we must maximize that angle. The same can be concluded from the dependence $\psi_m(\alpha)$ that is plotted in **Figure 7**.

However, when α approaches the value $\alpha_{lim} = \arcsin(1/N_m)$, total inner reflection appears at the output waveguide face, and the mode is reflected back to the waveguide (to the side sample face) instead of being emitted out through the output sample face. That limit value is marked in the graph with the dash line. Proper choice of the angle α should be performed considering the maximal refractive index value, which is expected to be obtained into the sample by the applied method of waveguide fabrication. Slightly overestimated value of that refractive index is substituted for N_m to the expression for α_{lim}. Being calculated in such a manner, angle limit represents the optimal value of the angle α. Indeed, as the mode indices are always less than the maximal refractive index in a waveguide, described manner of the bevel angle choice prevents the occurrence of total inner reflection at the output sample face for all modes of the examined waveguide.

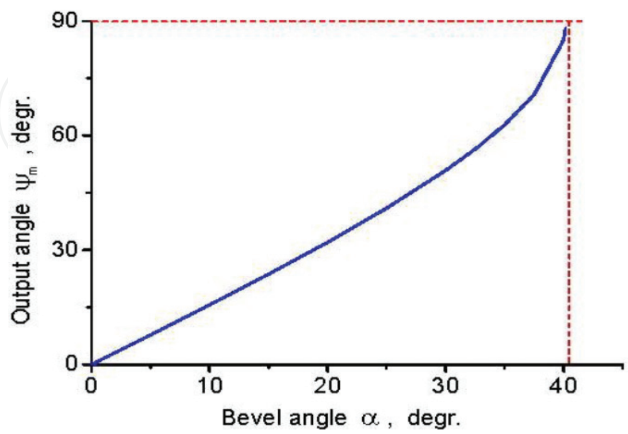

Figure 7. Influence of the sample bevel angle on the sensitivity of measuring. $N_m = 1.55$.

http://dx.doi.org/10.5772/intechopen.75558

3.2. Requirements to the collimator

Adjustment of the collimator must provide acceptable divergence of the collimated light beam. Let us first consider the axial section of that beam by the plane normal to the waveguide surface (the upright plane YZ in **Figure 2**). One can conclude from the drawn ray scheme that divergent (in that upright projection) beam causes a mismatch between apertures of waveguide mode and exciting focused spatial light beam. That mismatch results in decreasing the excitation efficiency. However, it does not influence on the registered angular values (they are measured into another planform projection XZ). Now let us consider the affect of beam divergence into that plane XZ (that coincides with the sample surface) on the results of angular measurements. One can conclude from **Figure 3** that if a divergence of the incident light beam is small, each output beam acquires a slight angular broadening, but it remains approximately axisymmetric relatively to the direction ψ_m. Therefore, registration of the central direction of each weakly divergent output light beam eliminates the affect of possible small maladjustment of the collimator.

Another requirement concerns performances of examined waveguides: the divergence of each output beam must be less than the angles between the output beams corresponding to waveguide modes of adjacent orders. Otherwise, overlapped different beams could not be distinguished and measured. Let us evaluate these angles basing on performances of graded-index waveguides which mostly demonstrate the closer mode indices (and, hence, would form the least beam spatial separation in the considered scheme) for higher-order modes. Considering the presented condition for the bevel angle α, we can deduce following expression from Eq.(1) for adjacent higher-order modes: $N_m - N_{m+1} \approx N_{max} \times (\psi_m - \psi_{m+1}) \cos \psi_{av}$, where $\psi_{av} = (\psi_m + \psi_{m+1})/2$. On the other hand, we obtain from Eq. (1) that $\cos \psi_m = [1 - (N_{av} / N_{max})^2]^{1/2}$ where N_{av} – the value corresponding to the mean direction between considered output beams, and $N_{av} \approx (N_m + N_{m+1})/2$. Hence the angle between those light beams $\delta\psi = \psi_m - \psi_{m+1} \approx (N_m - N_{m+1})/(N^2_{max} - N^2_{av})^{1/2}$. As an example, let us evaluate $\delta\psi$ for some planar graded-index waveguide fabricated by ion-exchanged diffusion in commercial glass. Defining the model values as $N_{max} = 1.53$, $N_{av} = 1.51$ and also $(N_m - N_{m+1}) = 10^{-4}$ for higher-order modes, we obtain $\delta\psi \approx 4 \times 10^{-4}$ radian ≈ 1.4 arcmin. So, the divergence of the collimated light beam must not exceed that limit. That condition can be easily met in adjusting the optical scheme.

Thus we can expect that the source of the main affect on the results could be deviations from the conditions of mode excitation occurring in the launching scheme unit.

3.3. Tolerance of incident beam direction

As Eq. (1) involves the angle of incidence i, that angle can be considered as a factor capable of affecting the reliability of the results of mode index measurements. Being considered together, Eqs. (1) and (2) allow evaluating the occurred errors caused by deviation of the incident beam from the condition of normal incidence to the input waveguide face. Indeed, in the basic measuring regime calculations of mode indices are executed according to Eq. (2). However, if the mode launching unit is adjusted inaccurately (i.e. when $i \neq 0$), substitution of measured values ψ_m to Eq. (2) leads to appearance of errors because the right way is application of Eq. (1) in this case.

Let us evaluate those errors. We can deduce from Eq. (2) that $\partial N_m/\partial\psi_m = (\cos\psi_m/\sin\alpha)$. Ray tracing that was performed for the scheme shown in **Figure 3** resulted in following $\psi_m(i)$ dependence: $\psi_m = \arcsin\{N_m \sin[\alpha - \arcsin(\sin i/N_m)]\}$. We could note that the operating variant of the measuring technique is the case $i \approx 0$. Then, considering negligibility of the angle i, the term $\partial\psi_m/\partial i$ can be written as $\partial\psi_m/\partial i \approx -\cos\alpha/\cos\psi_m$. Substituting that term into the expression for $\partial N_m/\partial\psi_m$ and defining $\Delta N_m = |\partial N_m|$, we can evaluate the mode index error as $\Delta N_m = \Delta i/\tan\alpha$. Here Δi denotes the increment of angle i from some value. Since we are considering the deviation from the condition of normal incidence of the input beam (i.e., from zero angle of incidence), just the small angle i plays itself the role of the increment Δi here. Then, replacing the values in the derived expression, we obtain the desired dependence of the mode index error on the angle of incidence:

$$\Delta N_m(i) = i/\tan\alpha \tag{5}$$

where i is a small angle in radian measure. This expression indicates that the mentioned mode index errors caused by wrong application of Eq. (2) in the case of deviation from the condition of normal incidence of the input light beam will be identical for all modes in the examined waveguide.

To confirm that unobvious conclusion, we can consider the described sample of K8: K^+ waveguide and evaluate numerically the mentioned errors by another manner. In this case we assume that considered mode index error can be defined as $\Delta N_m(i) = N_m - N'_m$, where N'_m is the incorrect value calculating according to Eq.(2) without involving the angle of incidence, and N_m is the actual mode index value. The mode indices measured by the traditional m-line spectroscopy technique (see **Table 1**) are substituted for those actual values. Defining the angle of incidence i as a variable and using the actual mode index values, we calculated from Eq. (1) the values of the output angle ψ'_m that would be obtained in measurements for the given angles i. Then we substitute those angles ψ'_m into Eq. (2) and find the corresponding N'_m values. The errors of mode index determination are obtained by comparing the actual mode indices with those calculated N'_m values. The results of determination of $\Delta N_m(i)$ values by that manner are shown in **Figure 8**.

It can be noted that the errors calculated for the modes of different orders are really identical in the most practical cases of small angles of incidence. The $\Delta N_m(i)$ dependence obtained for that waveguide sample by calculation according to Eq. (5) coincides completely with the one shown in this figure. So, the obtained results confirm a validity of the derived Eq. (5), and it can be applied for evaluation of mode index errors. We can note here that precise adjustment of the used GS-5 goniometer sample mount in our experiments allowed limiting the values of the angle of incidence within the range of 5 arcsec. Therefore the mentioned errors do not exceed 3×10^{-5}, and that is quite acceptable value corresponding to the usual level of errors occurred in measuring by the traditional m-line spectroscopy technique.

One can also see from Eq. (5) that the choice of the bevel angle α closer to the upper limit value makes it possible not only to increase the sensitivity of the end-fire mode spectroscopy

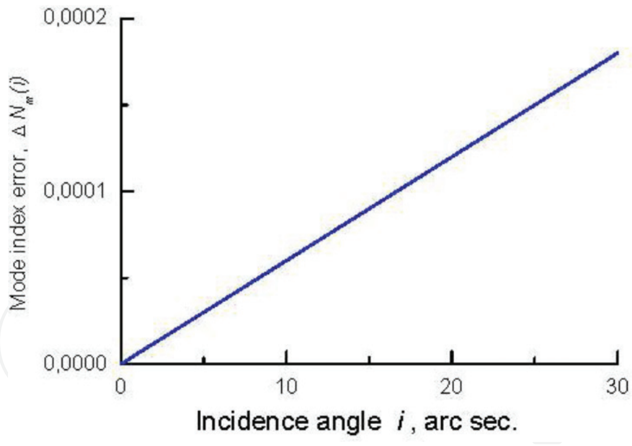

Figure 8. Errors caused by deviation from the condition of normal incidence of exciting beam.

technique but also to reduce the influence of deviation from the condition of normal beam incidence to the input waveguide face.

3.4. Adjustment of input cylindrical lens

Besides the inclination of the incident beam in the XZ plane, occurrence of some turn of the cylindrical lens generatrix relatively to the waveguide plane in the launching scheme block is possible in measuring. Let us consider that case of the lens rotated around its optical axis assuming that the lens axis is directed along the normal to the input sample face. The ray paths in waveguide mode excitation procedure are shown in **Figure 9**.

Let the lens generatrix be tilted toward the surface of the sample by angle γ. Then the plane of incidence of the focused light beam (that involves the two-sided arrow denoting the lens in the scheme) is turned to the vertical Y axis by the same angle as it is shown in **Figure 9**. Considering reversible character of light paths in optical systems containing the passive

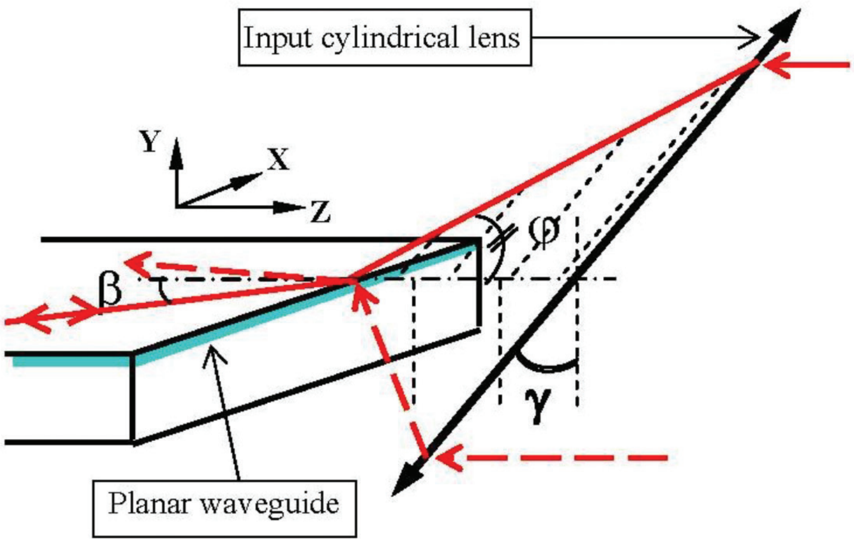

Figure 9. Waveguide mode excitation under the turn of input cylindrical lens.

elements only, we can consider our case in the reverse direction as an emission of the waveguide mode from the output waveguide face. That approach allows using the reasons and the results described above.

It is shown that the output mode beam looks like a curved light strip on the cross screen when a skew incidence of collimated beam to the output face is performed into the waveguide, and the strip edges demonstrate maximal inclinations from the longitudinal upright section. Then our studied case can be considered as reversible one – the tilted boundary rays of the incident light beam formed with the turned cylindrical lens excite the mode which is directed at some angle to the normal to the input sample face (see **Figure 9**) while the paraxial rays of the incident beam still meet the condition of normal incidence. That means excitation of divergent (in the planform XZ plane) waveguide mode beam, and consequently the spatial light beam which is radiated from the opposite output sample face should demonstrate angular broadening into that XZ projection.

If the numerical aperture of the exciting lens, as well as the size and position of the light spot at the input sample face are matched with the corresponding parameters of the excited mode, the output light beam is approximately axisymmetric relatively to the direction of unperturbed output beam, and that produces no additional errors neither in measuring the output beam direction nor in further calculation of the mode index. However, a set of waveguide modes is excited usually with the end-fire technique, and there is a natural wish to use this circumstance by measuring the characteristics of several modes under the single adjustment procedure. For this purpose, one scans the input end with the focused input beam and chooses a beam position that leads to optimizing the visibility of the mode's set. Then only the part of the shifted incident beam actually excites some individual mode. As the exciting lens is turned in the considered manner, the output light beam is broadened asymmetrically (relatively to the output mode direction that could be in the case of zero lens turn) as can be seen in **Figure 9**. Just that reason leads to additional errors in measuring. The detailed procedure of determination of dependence $\Delta N_m(\gamma)$ is presented in Ref. [15]. Here we show in **Figure 10** the example of that dependence calculated for the waveguide K8: K^+ considered above. Unlike the error type described in the preceding paragraph, one can see that the errors caused by lens turning differ one from another for modes of different orders, and the lowest-order mode indicate the minimum error. The noted difference between the errors decreases as the mode order increases, and for the two highest modes the mentioned errors almost coincide.

Whereas the considered error $\Delta N_m(\gamma)$ is substantially less than the error $\Delta N_m(i)$ for identical values of the angles i and γ, the former error caused by the lens turning dominates in practice because the used standard equipment provides precise control of normal light incidence to the sample face, but does not enable accurate orienting the lens generatrix relatively to the sample surface. In those cases the expected errors of the lens orientation could be up to the order of arc minutes, and therefore just that range of angle γ variations is used in the graph shown in **Figure 10**. It is seen that mode index errors are rather significant for those angles γ, and, in order to keep the errors within acceptable limits (no greater than 10^{-4}), one should try to control the orientation of the cylindrical lens with accuracy of about 2–3 arcmin.

http://dx.doi.org/10.5772/intechopen.75558

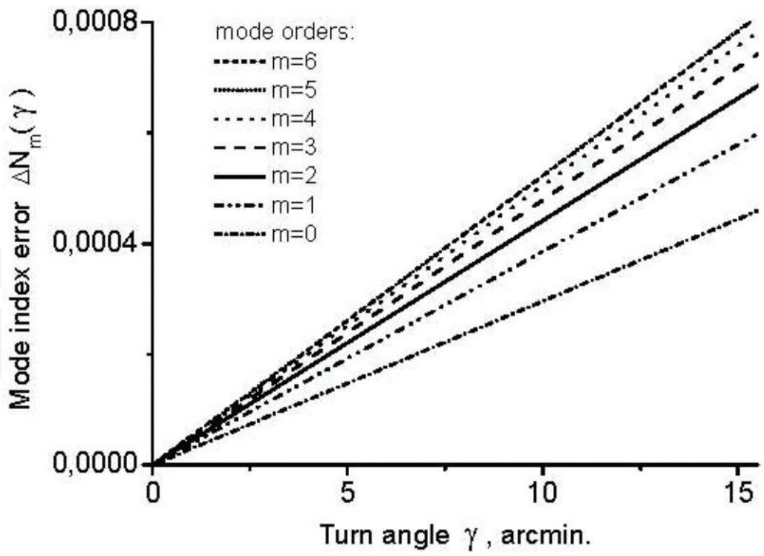

Figure 10. Errors caused by the turn of input cylindrical lens.

For tuning the lens turn, a rather simple technique associated with a variant of autocollimation method could be suggested. The performed procedures are illustrated by **Figures 11** and **12**.

First the tilt of the incident light beam should be registered by watching through the goniometer telescope or with the photoreceiver matrix. Then the reference glass cube (given in the goniometer tool kit) is installed on the goniometer sample mount, and the reflected light beam is registered near the opposite direction according to the scheme in **Figure 11**. Registered light strip patterns are shown in **Figure 12**.

If the measuring system is misadjusted in parameter γ, the strips representing direct and reflected beams demonstrate opposite inclinations at the angle of 2γ to each other. Turning

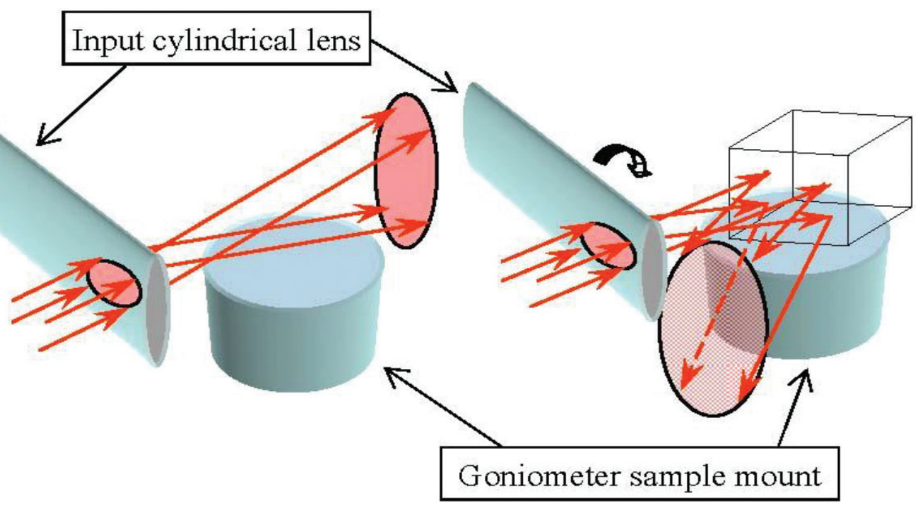

Figure 11. Adjusting the orientation of input cylindrical lens under consecutive registration of direct and reflected light beams.

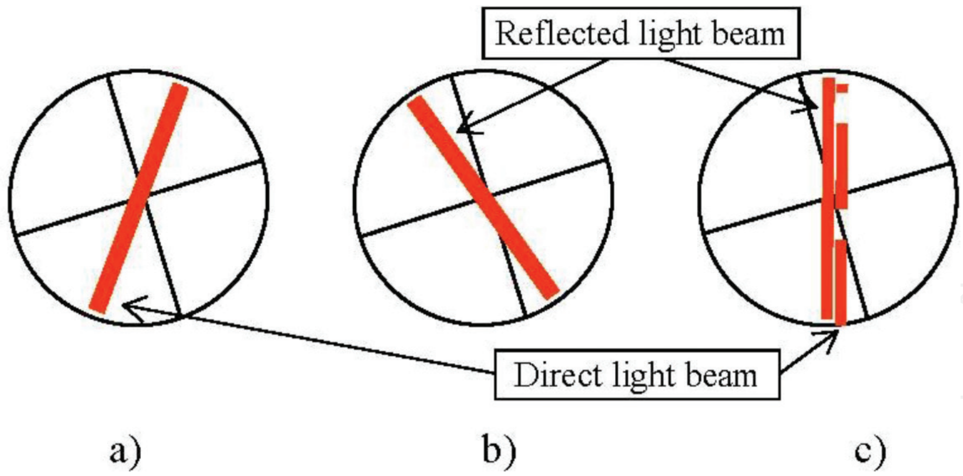

Figure 12. Patterns from the goniometer telescope in adjusting procedure: Direct (a) and reflected (b) light beams before, and also after (c) the procedure.

the lens around its ax and repeating the procedures one can obtain coincidence of orientations of those light strips. This will be the criterion for correct orientation of the cylindrical lens – the lens generatrix gets right orientation parallel to the sample mount surface. For example: using the micrometer ocular of the goniometer tool kit we were able to adjust the lens orientation with the accuracy of 2 arcmin. It can be concluded from the dependences shown in **Figure 10** that the corresponding mode index errors are reduced to an acceptable level. We can also note that our evaluation results in the maximum level of the measurement errors when the cylindrical lens is rotated around the axis, accompanied by the displacement of the input beam as it scans over the end of the waveguide. The mode index errors decrease as the incident beam is shifted toward the position that matches the region of localization of the measured mode, and the range of allowable lens tilts is broadened.

4. Conclusion

The presented materials prove applicability of the end-fire mode spectroscopy technique to analysis of planar optical waveguides with arbitrary cross refractive index profiles, and performed measurements of the characteristics of buried waveguides highlight this advantage of the technique. Furthermore, the technique allows conducting reliable direct complex measurements of the set of important optical characteristics of arbitrary planar waveguides (the mode spectrum and the maximal refractive index) in a single procedure. End-fire mode spectroscopy has a good potential for wide practical application in examinations of planar structures. Further developments should be aimed at modifying the measuring scheme in order to be able to analyze 3D optical guides. That could allow extending the area of technique applications by involving additional large group of waveguides including optical fibers.

Author details

Dmitry V. Svistunov

Address all correspondence to: svistunov@mail.ru

Peter-the-Great St.-Petersburg Polytechnic University, St.-Petersburg, Russia

References

[1] Tien PK, Ulrich R. Theory of prism-film coupler and thin-film light guides. Journal of the Optical Society of America. 1970;**60**(10):1325-1337. DOI: 10.1364/JOSA.60.001325

[2] Barnosky MK. Introduction to Integrated Optics. NY, London: Plenum Press; 1974. 515 p. DOI: 10.1007/978-1-4684-2082-1

[3] Wang X, Yin C, Cao Z. Progress in Planar Optical Waveguides. Berlin-Heidelberg: Springer-Verlag; 2016. XI,241 p. DOI: 10.1007/978-3-662-48984-0

[4] Lavchiev VM, Jakoby B, Hedenig U, Grille T, Kirkbride JMR, Ritchie GAD. M-line spectroscopy on mid-infrared Si photonic crystals for fluid sensing and chemical imaging. Optics Express. 2016;**24**(1):262-271. DOI: 10.1364/OE.24.000262

[5] Yulianto M, Marzuki A, Suryanti V. Diffusion processes for planar waveguides fabrication in soda-lime glasses. Journal of Physics: Conference Series. 2017;**909**(1):012022 (5 pp). DOI: 10.1088/1742-6596/909/1/012022

[6] White JM, Heidrich PF. Optical waveguide refractive index profiles determined from measurement of mode indices: A simple analysis. Applied Optics. 1976;**15**(1):151-155. DOI: 10.1364/AO.15.000151

[7] Chiang KS. Construction of refractive-index profiles of planar dielectric waveguides from the distribution of effective indexes. Journal of Lightwave Technology. 1985;**LT-3**(2):385-391. DOI: 10.1109/JLT.1985.1074194

[8] Rogozinski R. Determination of refractive index profiles of planar buried waveguides on the basis of a set of modal propagation constants. Optics Communication. 2003; **219**(1):199-214. DOI: 10.1016/S0030-4018(03)01286-0

[9] Marangoni M, Osellame R, Ramponi R, Giorgetti E. Second harmonic generation from radiation to guided modes for the characterization of reverse-proton-exchanged waveguides. Opitcs Express. 2004;**12**(2):294-298. DOI: 10.1364/OPEX.12.000294

[10] Glebov LB, Dokuchaev VG, Morozova IS. Simple method for reconstruction of refractive-index profile for planar wave-guides. Optics and Spectroscopy. 1989;**66**(5):1110-1114. WOS: A1989AC80700031

[11] Monir M, El-Refaei H, Khalil D. Single-mode refractive index reconstruction using an nm-line technique. Fiber and Integrated Optics. 2006;**25**(2):69-74. DOI: 10.1080/01468030500466230

[12] Svistunov DV. End-fire mode spectroscopy technique of examination of planar waveguides. Journal of Optics A: Pure and Applied Optics. 2008;**10**(8):085301(4 pp). DOI: 10.1088/1464-4258/10/8/085301

[13] Svistunov DV. New measuring method of examination of planar optical waveguides. In: Proceedings of Progress in Electromagnetics Research Symposium (PIERS 2009 in Beijing); 23-27 March 2009; Beijing. 2009. pp. 1689-1693. DOI: 10.2529/PIERS080904135015

[14] Zolotov EM, Kiselyov VA, Pelekhaty VM. Determination of characteristics of optical diffuse waveguides. Soviet J Quant. Electr. 1978;**8**(11):2386-2382. DOI: 10.1070/QE1978v008n11ABEH011261

[15] Svistunov DV. Optimizing the mode-excitation conditions when a planar waveguide is being investigated by means of end-fire mode spectroscopy. Journal of Optical Technology. 2014;**81**(1):1-5. DOI: 10.1364/JOT.81.000001